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I. E.

THE VANDERBILT UNIVERSITY FREE-ELECTRON LASER CENTER

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Abstract

Vanderbilt University has established a multidisciplinary Free-Electron Laser Center to exploit the opportunities made possible by the free-electron laser for applications in medicine, biology, materials science, and other fields of research. The free-electron laser, which recently began operation, is tunable over the wavelength range from 2 to 10 μm. The device has demonstrated 400 mJ per pulse at a wavelength of 4.8 μm, in 6-μs pulses, and an average power of 11 W at a repetition rate of 30 Hz. Extensions to the X-ray and far-infrared regions are underway. The Center, which will be used by researchers from within the University and from around the world, has already given birth to a variety of interdisciplinary collaborations among scientists brought together by the unique opportunities provided by the Center.

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1. THE FACILITY

The Vanderbilt University Free-Electron Laser Center is dedicated to exploring the application of free-electron lasers to research in medical and materials sciences. The free-electron laser is located in a new laboratory building located on the University campus adjacent to the Departments of Physics and Chemistry, the School of Engineering, and the School of Medicine. The Department of Molecular Biology is close by. The Center houses not only the free-electron laser, but a variety of experimental laboratories and supporting equipment as well.

A cross-sectional view of the facility is shown in Fig. 1. As indicated there, the free-electron laser is located in a vault in the sub-basement. The control and diagnostic rooms are located on the laboratory level, as indicated in Fig. 2. The control room contains the Sun 386i master control computer as well as the laboratory radiation and laser safety systems. The diagnostic room is used to monitor the performance of the free-electron laser, including the power, the pulse energy, and the spectrum of the laser on a single shot.

The laboratory level provides approximately 600 m^2 of laboratory space. Five laser target rooms are equipped with general-purpose utilities such as conditioned and isolated power, deionized water, and computer interconnections. An optical-beam transport system designed and built by Optomec Design Company is used to bring the beam from the free-electron laser through the diagnostic room to the various experimental laboratories, as indicated in Fig. 2.

For experiments in surgery, the Center has a complete medical suite. The two operating rooms are built in accordance with American Association for Laboratory Animal Science guidelines and the facility has been approved for animal surgery. The first operating room has been equipped with an operating table and lamp, a complete range of conventional surgical instruments, anesthesia machine, I. V. pump, drill, electrocautery unit, a bank of electrophysiological instruments for assessing laser effects on nerve and brain, and other conventional surgical equipment. In addition, for use with the free-electron laser, the operating room is equipped with an articulated arm, which provides a hand-held optical-beam delivery system to manipulate the free-electron laser beam in surgical procedures, and a Zeiss operating microscope. The second operating room will be equipped later, based on experience with the first operating room. In addition to the operating rooms, the medical suite includes a computer work room for computer-image-guided surgery, lockers for the surgeons, and an approved animal-care facility for the preparation and recovery of the animals used in surgery.

These laboratory facilities are supplemented by a variety of support laboratories in the Center which have special-purpose equipment. A wet lab and a tissue-culture lab are provided to support experiments in biology and medicine. These laboratories are presently equipped with biological and fume hoods, incubators, microscopes, chromatographs, refrigerators, centrifuges, and so on. In addition, an electronics shop is available for the maintainance and development of experimental equipment.

The Center also possesses a combination of instruments which are directly available to the applications experiments. Major items of equipment include a Raman spectrometer, doubled-YAG-pumped dye laser system, excimer laser system with articulated arm and fiber delivery systems, cw modelocked Yag laser, argon laser, fluorescence spectrometer, and FTIR spectrometer. Other facilities and equipment are available through the Dapartments and Schools of the University which are collaborating in the research at the Center.

2. THE FREE-ELECTRON LASER

The Vanderbilt free-electron laser is a model FEL I built by Sierra Laser Systems. This is a small, infrared free-electron laser similar to the Stanford University Mk. III free-electron laser[1]. The electron beam is produced by a 45-MeV rf accelerator operating at a frequency of 2.856 GHz. The rf pulses are variable in length up to 8 μs, overall, and the electron-beam pulses last up to 7 μs. The nominal and measured operating parameters of the laser are summarized in Table I.

The laser pulse length is variable up to about 6 μs, and the repetition rate is variable up to 60 Hz. Each macropulse consists of a sequence of mode-locked micropulses, each about 2 ps in length, repeated at the accelerator frequency of 2.856 Ghz. The wavelength is tunable from 2 to 10 μm on the fundamental, and down to about 1 μm on the third harmonic. The power is maximum around 4 μm, and falls off at longer and shorter wavelengths. Recent experiments have demonstrated pulse energy of 400 mJ in pulses lasting 6 μs, at a wavelength of 4.8 μm. A typical macropulse is shown in Fig 3. Operating at a pulse repetition frequency of 30 Hz, a sustained average power of 11 W has been achieved, making the free-electron laser the most powerful in the world.

For maximum flexibility, the FEL 1 is computer controlled by a Sun 386i master computer and three slave computers. For the convenience of the users, it is possible to control the laser from remote computer terminals located in the experimental laboratories.

Although operation as summarized in Table I is well suited to a broad variety of applications, as described in Section 4, other applications demand a variety of other wavelengths and pulse lengths. This will require that the free-electron laser be modified in several ways, with a priority to be established by the demands of the various applications. The following upgrades are in progress, and others may be considered in the future:

Monochromatic (but incoherent) X-rays are important for a variety of applications including hard-X-ray medical imaging and therapy and soft-X-ray microscopy. These X-rays will be produced by Compton backscatter of free-electron laser photons off the electron beam. The electron beam downstream of the wiggler is focused to a 20-μm spot to interact with the focused laser beam. The electron beam may be directed upward toward the laboratory level, as shown in Fig. 3, since the X-rays are produced in this same dircetion. Alternatively, the X-rays themselves may be directed toward the laboratory by means of X-ray hollow-fiber optics. The X-rays are transmitted to the target room by means of a tube through the concrete radiation shielding. The X-ray facility will initially produce of the order of 10^{10} photons/s in a spot a few centimeters in radius, at wavelengths from 1 nm (1 keV) to 0.06 nm (20 keV).

Far-infrared wavelengths are needed for experiments in biophysics and materials physics. To address these requirements, it is planned to develop a Cerenkov free-electron laser source able to operate in the wavelength region from 50 to 200 μm. A Cerenkov free-electron laser operates by interacting the high-energy electron beam with an electromagnetic wave travelling at the same velocity as the electrons, slightly less than the speed of light, in a dielectric waveguide[2]. The peak power is predicted to be of the order of 10 MW in the micropulses. It will be possible to operate the Cerenkov free-electron laser synchronously with the conventional free-electron laser for pump-probe experiments.

For some experiments, in time-resolved spectroscopy, for instance, it is useful to have shorter macropulses, or even single micropulses. Short macropulses, of the order of 10-ns duration, can be achieved by cavity dumping using a laser-driven silicon output coupler in the optical cavity of the free-electron laser[3]. When the photoelectric injector or pulse chopper is used, single micropulses can be obtained by switching out a single micropulse from the macropulse or by cavity dumping.

Wavelengths shorter than the nominal 2-μm limit of the Sierra Laser Systems FEL I are needed for experiments in materials physics, biophysics, and surgery.

Wavelengths down to about 1 μm, in the near infrared, may be obtained by lasing on the third harmonic of the free-electron laser[4]. Shorter wavelengths, down to the near ultraviolet, may be obtained by conventional nonlinear harmonic generation techniques[5].

For applications in materials physics, molecular dynamics, biophysics, and molecular biology, it is sometimes useful to have micropulses shorter than the nominal 2 ps of the Sierra Laser Systems FEL I. Three techniques will be developed to provide pulses as short as a few optical cycles, tunable throughout the infrared. In the first technique, the electron-beam energy will be chirped within the micropulses to generate chirp in the laser micropulses. This chirp may be used in a dispersive delay line (a grating pair) to compress the optical pulses to a few cycles[6]. In the second technique, the synchrotron instabilities may be used at long wavelengths to compress the pulses within the free-electron laser itself. Finally, at short wavelengths, nonlinear optical fibers may be used to generate a wavelength chirp so the optical pulse may be compressed in a dispersive delay line, as is done with conventional lasers.

3. APPLICATIONS RESEARCH AT THE CENTER

The Center currently supports a broad program of research in medicine and materials science. The experiments in progress are characterized not only by the close relationship between experiments but also by the degree of collaboration between the scientists working on the various projects at the Center. It may be that the most important contribution of Centers such as the one at Vanderbilt will be to bring together investigators from different fields and orientations and cross fertilize projects with ideas which would not have been introduced in the normal course of research. Projects underway at the Center include the linear and nonlinear interaction of laer radiation with optical materials and mammalian tissue, the spectroscopy of species adsorbed on surfaces, the linear and nonlinear spectroscopy of DNA and RNA, the dynamics of proteins in cell membranes, the biomodulation of wound healing by lasers, image-guided stereotactic neurosurgery, and the use of monochromatic X-rays in medical imaging and therapy.

In addition to supporting intramural research, the Center has been established as an international resource to support a broad extramural research program. The selection of programs for the Center and the allocation of the resources of the Center to these programs is the responsibility of the Peer Review Board of the Center.

Applications to use the Center should be directed through the Director of the Center. Proposals will be accepted in the following categories:

Medical research, including surgery, photodynamic and radiation therapy, medical imaging and diagnostics, and other medical therapy or diagnostics;

Biology, including biophysics, biochemistry, and molecular biology;

Materials science, including optical materials, surface physics and chemistry, laser-materials interactions, condensed-matter physics, radiation damage, and related science and engineering.

To be considered, a proposal must make good use of the Vanderbilt free-electron laser, and must compliment the program underway or planned for the Center. Although not a requirement, collaboration with other experimenters at the Center is encouraged as this will facilitate the conduct of the experiments and lead to cross-fertilization. Projects meeting these criteria will be prioritized by the Peer Review Board based on generally accepted standards of scientific merit and importance. In 1992 and 1993, the Peer Review Board will also be responsible for funding extramural projects using the Vanderbilt free-electron laser. The procedure for applying for funding under this program is similar to that described above.

Acknowledgement

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Table I: Parameters of the Sierra Laser Systems FEL I free-electron laser.

	Nominal	Measured
Accelerator		
Electron energy	20-45 MeV	36-43 MeV
Micropulse peak current	20-40 A	
Macropulse average current	200 mA	250 mA
Energy spread	0.5%	0.5%
Normalized emittance	4πx10π mm-mrad	
Wiggler		
Wiggler length	108 cm	108 cm
Wiggler period	2.3 cm	2.3 cm
Maximum wiggler field (rms)	0.47 T	0.44 T
Laser		
Wavelength	2-10 μm	2.6-5.6 μm
Micropulse duration	0.5-3 ps	
Micropulse repetition rate	2.9 GHz	2.9 Ghz
Macropulse duration	0.5-6 μs	6 μs
Macropulse energy	100 mJ	400 mJ
Macropulse repetition rate	0-60 Hz	1-30 Hz
Overall average power	0-6 W	0-11 W

Figure captions:

Fig. 1. Cross-sectional view of the Vanderbilt University Free-Electron Laser Center.

Fig. 2. Plan view of the vault level of the Vanderbilt University Free-Electron Laser Center.

Fig. 3. A typical macropulse from the FEL I laser.

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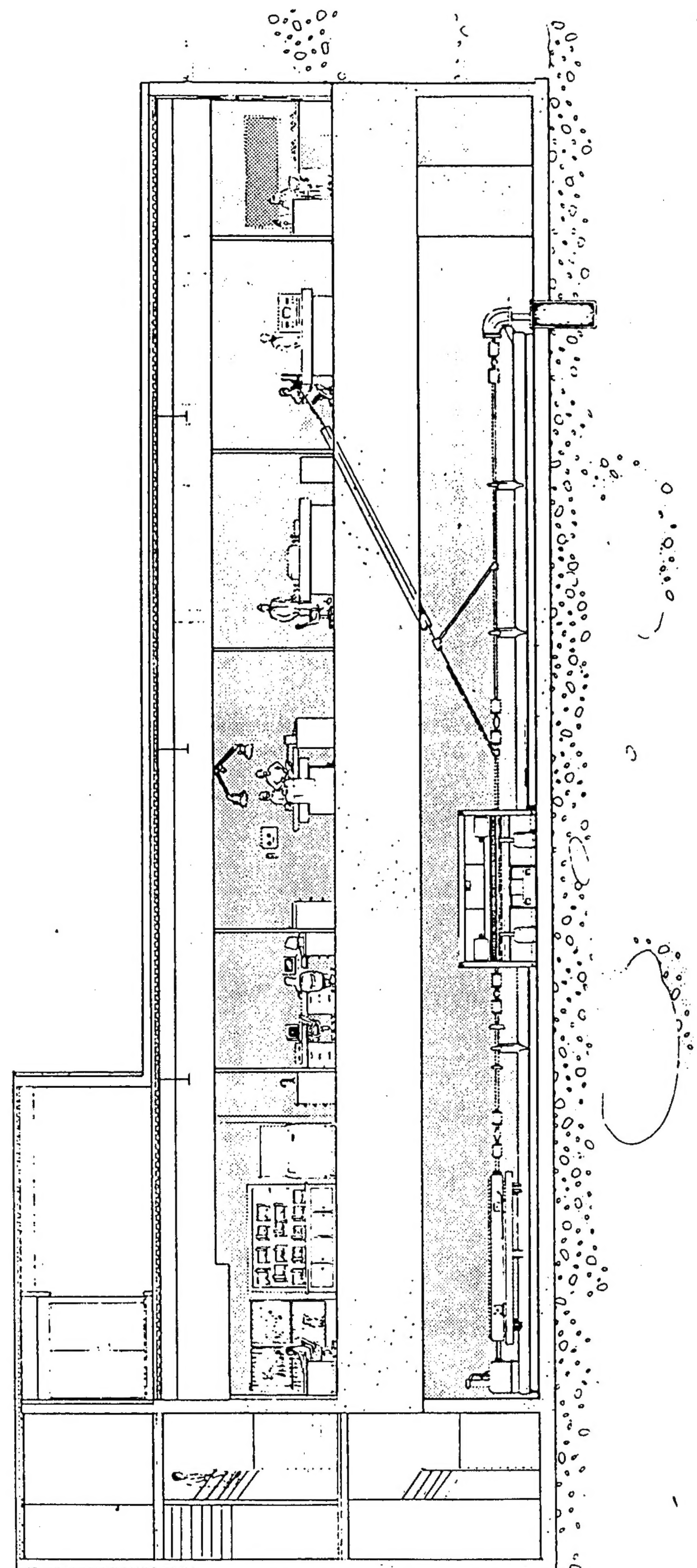
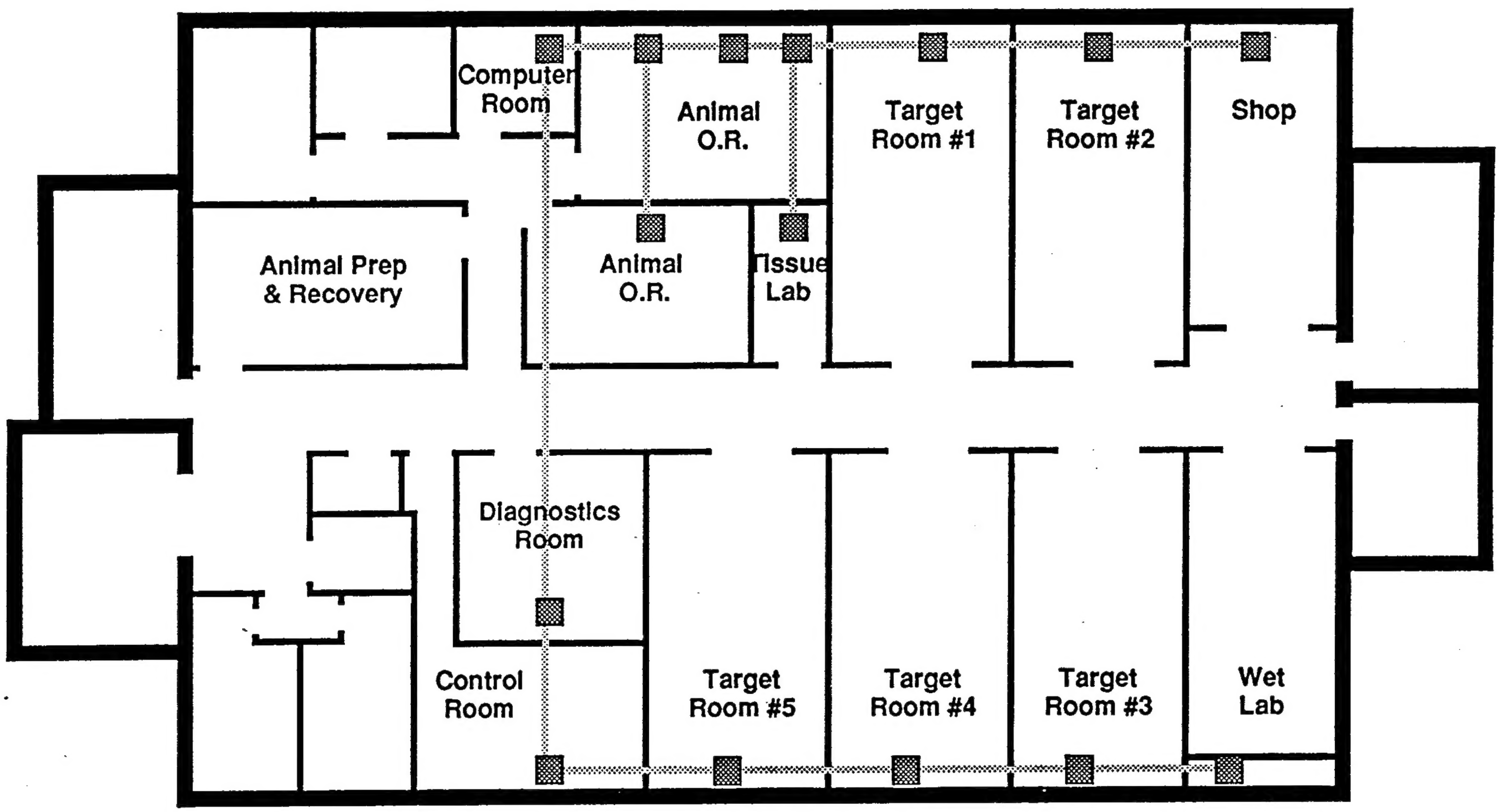
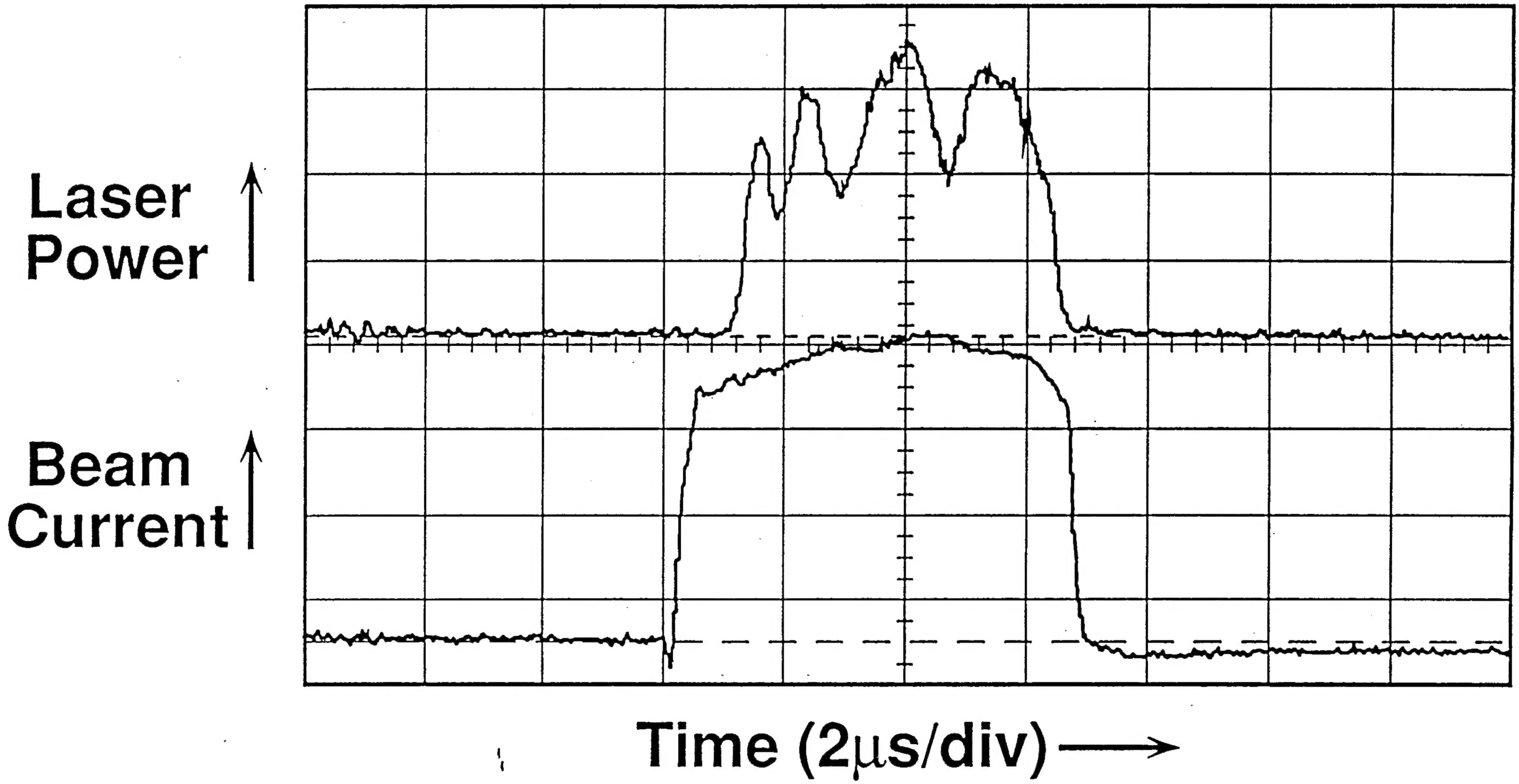


VANDERBILT FREE-ELECTRON LASER CENTER
BEAM TRANSPORT SYSTEM




Laser Power
Beam Current
Time (2μs/div)